Coastal Protection and Development Planning Guidelines for Bermuda

Submitted to the

Government of Bermuda, Ministry of the Environment

By

SMITH WARNER INTERNATIONAL
COASTAL & ENVIRONMENTAL ENGINEERING

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Executive Summary

Background

At an estimated 3,000 people per square mile, Bermuda is one of the most densely populated places in the world. However, with an economy based on offshore financial services and tourism, Bermuda also enjoys one of the highest per capita incomes in the world. Unfortunately, this financial success, combined with the limited land space, has resulted in considerable development pressure on the island. In particular, the island's 180 miles of coastline are in high demand for development.

Running in tandem with this increasing demand, Bermuda's coast has been experiencing erosion, and it is evident that in many areas around the island there is a need for shoreline protection. In fact, in recent years the Government of Bermuda (GOB) has seen an increase in the number of applications for permits to carry out beach and shoreline protection works, and for structures or developments to be sited adjacent to, or on the coast.

While the GOB has a vested interest in the protection of the island's shoreline and associated coastal property from erosion, it is recognized that this interest must go hand in hand with the protection of the coast from inappropriate development, in order to retain the coast's natural appearance. As such, the GOB has sought guidance on the most suitable shoreline protection practices for the Bermuda situation, and has contracted ***Smith Warner International*** (SWI) to conduct a *Coastal Erosion Vulnerability Assessment* and to Prepare *Coastal Protection and Development Planning Guidelines for Bermuda*.

This document presents the Development Planning Guidelines for Bermuda and includes recommendations for appropriate shoreline protection and typical designs for suitable coastal structures. Information is also given on other important issues that should be considered in the planning of development along the Bermuda coastline, including inundation levels and the control of biological agents of erosion.

Context of the Guidelines

These coastal protection and planning guidelines have been created with the primary purpose of supporting the Bermuda DOP in their review of the 1992 Bermuda Plan. The intention is to make the Development Plan Review (DPR) better informed with respect to the implementation of coastal development and protection works.

Consideration has therefore been given to the contents of the existing Bermuda Plan 1992 and what currently obtains for the planning and implementation of coastal development and protection works. Importance has also been placed on the preservation of the Bermuda Image, and the GOB's desire to maintain the natural appearance of the island wherever possible.

The development of the following guidelines was also aided significantly by the observations and lessons learned after the passage of Hurricane Fabian in September 2003. For example, several of the structural design recommendations made in Section 3 of this document have been enhanced by the findings of the *Assessment of Coastal Damages from Hurricane Fabian*, submitted by SWI to the GOB in October 2003.

Finally, the conclusions and findings presented in the companion report to this document, *The Bermuda Coastal Erosion Vulnerability Assessment – Final Report* have been incorporated into many of the shoreline development recommendations proposed in Section 4 of this document.

Appropriate Shoreline Protection

By their very nature coastlines are dynamic -they have been changing as long as there have been coastlines. However, as populations have grown, and the demand for seaside development has increased, there has been greater pressure to 'protect' shorelines from the forces of nature. Some argue that attempts to subdue or contain the ocean are futile given the magnitude of the wind and wave forces active along coastlines. They believe that instead of interfering with the dynamics of coastlines, nature should be allowed to take its course and develop away from the active forces of the shore, as nature will inevitably win.

On the other hand, in places such as Bermuda where landspace is finite and subject to the forces of erosion, there is an imminent need to armour the shoreline in order to protect life, property and infrastructure. A balance must therefore be sought in islands such as Bermuda between respecting the forces of nature and protecting human life and assets.

The key to achieving this balance is to ensure that the approach to armouring and development along the shoreline is cognizant of the forces of nature acting in the particular locations during a period of time.

Appropriate Shoreline Development

Among the concepts to be applied to coastal development include the establishment of setbacks with consideration to the determined inundation levels, the adoption of a community approach to shoreline defense, and the importance of functional integrity over aesthetics.

Ecological Considerations

There are three significant ecological features to be considered in the management of erosion in Bermuda: The *Casuarina* trees, boring organisms in Harrington Sound, and the Coral Reefs.

In order to address the problem of the *Casuarina*, and to mitigate the erosion caused by these trees, an appropriate Eradication Programme and Public Awareness Campaign need to be developed. These initiatives should seek to remove the *Casuarina* in the coastal areas and replace them with an endemic species such as the Bermuda Cedar.

The action of **boring and grazing organisms** such as gastropods, bivalves and worms living in rocks within the intertidal zone removes significant rock material over time to form a distinct notch along the coastline of Harrington Sound. Research needs to be conducted into the specific eroding organisms in Harrington Sound to determine their biology and ecology in order to develop appropriate management strategies. Until such research and plans are developed, shoreline protection will need to be considered on a case by case basis.

The importance of the **rim and boiler reefs** to the protection of Bermuda's shoreline cannot be overstated. Their dominance of the coastal zone, and their role in slowing day to day wave action and dissipating wave energy is vital in the maintaining of sandy and rocky shorelines of islands. Without the reefs, the wave energy reaching Bermuda's shores would be much greater, and have a major effect on the stability of the islands. Based on their extremely important role in the protection of the shoreline, it is essential that the health and structure of these reefs be maintained.

Conclusions

Bermuda's coastal environment is under increasing development pressure, despite the island's exposure to significant shoreline erosion during storm conditions. Buildings need to be designed and constructed to protect human life and assets giving due respect the prevailing forces of nature. With appropriate planning regulations and building practices, Bermuda's coastline properties can be protected from damage and a natural or semi-natural appearance preserved. These Guidelines provide the necessary information and a solid foundation for the formulation of appropriate shoreline protection and development policies in Bermuda.

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Acronyms

DOP	Department of Planning
DPR	Development Plan Review
GOB	Government of Bermuda
SWI	Smith Warner International

1. Introduction

1.1. Background

Located in the North Atlantic Sea, Bermuda is a small island of only 21 square miles with a population of approximately 65,000 people. At an estimated 3,000 people per square mile, this makes Bermuda one of the most densely populated places in the world. However, with an economy based on offshore financial services and tourism, Bermuda also enjoys one of the highest per capita incomes in the world. Unfortunately, this financial success, combined with the limited land space, has resulted in considerable development pressure on the island, leading to a dense mix of development zones. In particular, the island's 180 miles of coastline are in high demand for development.

Running in tandem with this increasing demand, Bermuda's coast has been experiencing erosion, and it is evident that in many areas around the island there is a need for shoreline protection. In fact, in recent years the Government of Bermuda (GOB) has seen an increase in the number of applications for permits to carry out beach and shoreline protection works, and for structures or developments to be sited adjacent to, or on the coast.

While the GOB has a vested interest in the protection of the island's shoreline and associated coastal property from erosion, it is recognized that this interest must go hand in hand with the protection of the coast from inappropriate development, in order to retain the coast's natural appearance. As such, the GOB has sought guidance on the most suitable shoreline protection practices for the Bermuda situation, and has contracted ***Smith Warner International*** (SWI) to conduct a *Coastal Erosion Vulnerability Assessment* and to Prepare *Coastal Protection and Development Planning Guidelines for Bermuda*.

This document presents the Development Planning Guidelines for Bermuda and includes recommendations for appropriate shoreline protection and typical designs for suitable coastal structures. Information is also given on other important issues that should be considered in the planning of development along the Bermuda coastline, including inundation levels and the control of biological agents of erosion.

1.2. Scope of Work

In 2001, when the GOB invited qualified firms to submit proposals for the conduct of the Coastal Erosion Vulnerability Assessment, they presented the objectives for the project as follows:

1. To provide a synthesis of the data that already exists in Bermuda about coastal erosion;
2. To determine which coastal areas in Bermuda are prone to erosion and which structures and landforms are most at risk;
3. To make recommendations of best practices for coastal development and conservation.

Based on these stated objectives SWI proposed to carry out the Erosion Vulnerability Assessment project in eight (8) discreet tasks (Presented in Appendix I of this document). The overall findings of the eight tasks and the project in general have been presented in a companion document, *The Bermuda Erosion Vulnerability Assessment – Final Report* (November 2004).

This document, *Coastal Protection and Development Planning Guidelines* has been prepared in fulfillment of the third objective for the overall project, and under Task 6 of the agreed scope of work for the study, which is presented following.

> *Task 6 – Preparation of Coastal Development Guidelines*
>
> *A comprehensive set of guidelines for assessing coastal development applications will then be prepared for the Department of Planning. These guidelines will address the issues of typical shoreline protection, stabilization, enhancement and maintenance. In addition to these guidelines, typical designs for the most appropriate shoreline protection will be prepared for different shoreline types. These guidelines will be presented in a manner compatible with the Draft Bermuda Development Plan.*

The report has been compiled with the understanding that the GOB Department of Planning (DOP) needs to have a sound knowledge of the design, construction, and maintenance requirements of coastal protection structures, so that only structures meeting specific design requirements, including consideration for the Bermuda Image, will be permitted. Such information is required so that the Bermuda Development Plan Review (DPR) may be informed as regards the implementation of coastal protection and development.

This document provides useful information on some of the general principles and procedures that should be considered for coastal works in Bermuda. It is not a detailed text on coastal engineering solutions, nor does it provide solutions that can be applied indiscriminately to any coastal property in Bermuda. Proper coastal solutions must be designed in relation to the local site conditions.

2. Context of the Guidelines

The SWI team made three project-specific visits to Bermuda (July 2003, September 2003 and July 2004), during which tours were conducted of the island by boat and on land, and meetings were held with a number of planning and coastal protection stakeholders. These tours and meetings facilitated the confirmation of the overall context for the development of the guidelines presented in this document.

As briefly mentioned in Section 1.2, these coastal protection and planning guidelines have been created with the primary purpose of supporting the Bermuda DOP in their production of the DPR. The intention is to make the DPR better informed with respect to the implementation of coastal development and protection works.

Consideration has therefore been given to the contents of the existing Bermuda Plan 1992 and what currently obtains for the planning and implementation of coastal development and protection works. Importance has also been placed on the preservation of the Bermuda Image, and the GOB's desire to maintain the natural appearance of the island wherever possible.

The development of the following guidelines was also aided significantly by the observations and lessons learned after the passage of Hurricane Fabian in September 2003. For example, several of the structural design recommendations made in Section 3 of this document have been enhanced by the findings of the *Assessment of Coastal Damages from Hurricane Fabian*, submitted by SWI to the GOB in October 2003.

Finally, the conclusions and findings presented in the companion report to this document, *The Bermuda Coastal Erosion Vulnerability Assessment – Final Report* have been incorporated into many of the shoreline development recommendations proposed in Section 4 of this document.

2.1. The Bermuda Plan 1992

The Bermuda Plan 1992 is the guiding planning statement for Bermuda, and was formulated for the purpose of regulating the use and development of land in Bermuda through to the year 2000 (except for Military Bases and the City of Hamilton).

The overall aim of the Plan is "*to maintain the quality of life in Bermuda by the wise use of resources and by effectively controlling and directing development so as to safeguard the environment, and as a consequence, the economic, cultural, social and general welfare of the people*."

The Bermuda Plan 1992 therefore addresses aspects of development ranging from details of planning, to design and landscaping, to specific zoning requirements. Of interest, Section 13 of the Plan addresses 'Other Forms of Development' including coastline development (Section 13.COA). However, this section of the plan lacks detail when compared to other areas of the document, and planners and other government officials are of the opinion that this gap in the guiding document has resulted in some of the coastal problems currently being experienced in Bermuda. This situation is compounded by the fact that no where else in the plan is consideration given to the appropriateness of coastal protection structures.

Section 13.COA (Forms of Development Coastline) addresses the following:

1. Applications for Coastal Development
2. General Direction to the Planning Board
3. Docks and Slipways
4. Floating Docks
5. Seawalls
6. Size of Docks
7. Standard Conditions

The only design considerations presented in this section of the plan are the maximum width (16ft) and areas (200ft^2) for docks and slip ways. Section 13 COA.5 mentions that *"sea walls may be permitted…..if the Board is satisfied that the scale, design and extent of any sea wall complies with the relevant provisions of Section 6"*. Section 6 of the plan addresses design and landscape, but gives no specific criteria applicable to coastal structures. These considerations are applied equally to all parts of the Bermuda shoreline despite geographical variations in exposure to storm conditions

2.2. The Bermuda Image

According to the Bermuda Plan 1992, The Bermuda Image refers to:

> "the appearance of Bermuda resulting from a harmonious mix of natural features and man-made elements which produce a visual quality and a character of development which are distinctively Bermudian, and which includes –
>
> a. A scale of building which is compatible with the landform and which sits comfortably in its setting;

b. The balance and proportions of the traditional building form as exemplified in sturdy residential structures with white pitched roofs, and features and embellishments which distinguish local architecture;

c. Plentiful, lush and colourful sub-tropical vegetation;

d. Gently rolling hillsides and dense vegetation which effectively blend and screen development and to maintain the illusion of open space and a natural appearance;

e. Bermuda stone walls, weathered rock cuts, hedging and planting alongside roads; and

f. Natural coves, bays, beaches, the rocky coastline and islands, with views and glimpses of vividly coloured waters and the ocean.

During meetings held with stakeholders, an issue which was repeatedly presented was whether or not the Bermuda Image has served to reduce or worsen the rate and forms of erosion experienced around Bermuda. Findings from the Coastal Erosion Vulnerability Assessment indicate that the primary cause of erosion is from wave action during storm events. Comparison of aerial photography over a long-term period has confirmed that day to day wave events do not contribute significantly to shoreline erosion. Rather it is only during more extreme events that beach and cliff erosion becomes noticeable.

In the development of sea defence strategies, to date much effort has been put into achieving conformance with the Bermuda Image. In practical terms, this has meant that seawalls when constructed may be either:

- Reinforced concrete faced with specific patterns; or
- Reinforced concrete faced with Bermuda stone; or

- Where low walls are to be constructed, walls may be made out of unreinforced Bermuda stone, held in place by mortar.

In most cases therefore, the treatment of seawalls to ensure conformance to the Bermuda Image has been largely cosmetic. From this viewpoint the conformance to this Image on these types of structures cannot be said to have contributed to the worsening of shoreline erosion. On the other hand, the desire to conform to this visual standard may have restricted the range or use of other shore protection options that may have been used.

As such, significant consideration has still been given to the Bermuda Image in the following sections of this document, and in particular in the finishes recommended for certain coastal protection structures. However, some effort has been made to expand the range of shore protection options considered.

2.3. Lessons Learned from Hurricane Fabian

On August 27, 2003 a tropical wave off the west coast of Africa developed into a tropical low, and then a tropical depression. By the next day, the weather system had organized and became Tropical Storm (TS) Fabian, the sixth named storm of the 2003 Atlantic Hurricane Season. On August 30, 2003 TS Fabian had strengthened and became Hurricane Fabian, a Category 3 hurricane, and the first major hurricane of the season.

Hurricane Fabian tracked westerly towards the Lesser Antilles, and then made a turn to the north, heading for Bermuda. On September 5th, 2003 the eye of Hurricane Fabian passed approximately 80 kilometers west of Bermuda, with the right quadrant of the storm hitting the island. Throughout the morning and afternoon of September 5th, Bermuda experienced sustained wind speeds of 190km/h, with gusts of up to 210km/h.

Hurricane Fabian caused significant damage to seawalls and shore protection structures throughout Bermuda, as well as substantial structural damage to houses built too close to the sea. The hurricane also resulted in the erosion of sand beaches and rock falls along cliffs and/or erosion of large blocks of cliffs due to fissures.

Hurricane Fabian provided this study with valuable first-hand experience of a major hurricane event on Bermuda's coastal environment.

2.3.1. Seawall failure

In general, two different modes of failure were observed for seawalls and shore protection structures. These included: impact forces, which broke apart the structure and scattered debris inland, and drawdown forces**,** where structures were overtopped, the backfill material eroded and the weight of the receding water resulted in overturning the structure in a seaward direction. Inadequately reinforced or non-existent foundations were also cited as contributory factors for these structural failures, or else where foundations were built on sand. At several sites, debris or parts from a failed seawall were carried inland, acting as projectiles and causing more severe damage to adjacent buildings, which would otherwise have only suffered from flooding damage. Shoreline damage was also observed to be often quite localized, with adjacent properties somehow avoiding damage. These could often be explained by differences in setback or elevation, or by inconsistencies in the type of shoreline protection employed. Progressive erosion was also thought to have resulted in the weakening of structures, eventually leading to their collapse in the storm. Finally, some structurally sound solutions were observed. These were characterized typically by properly reinforced concrete walls, which had been founded on rock.

2.3.2. Cliff Failure

The rock-falls that were observed along cliff-type shorelines ranged from minor to spectacular, in which single blocks weighing more than 50 tonnes had been eroded. This type of cliff failure puts infrastructure (buildings, roads, etc.) into a zone of increased risk. In general, however, the following agents of cliff failure were observed:

- Wave attack at the toe of the cliff, leading to oversteepening and/or instability in the upper layers;
- Through wave attack, the outer weathered and hardened layers of the Aeolian limestone had been stripped away, leaving a soft, sandy core exposed. Once these soft areas became exposed, erosion of the rock proceeded at a rapid pace during the storm;
- High-pressure jets of water (from breaking waves) were shot up through narrow vents in the cliff face rock. These jets weakened blocks of cliff face that would not normally have been exposed to wave action during the storm, thereby leading to cliff failure in elevated sections of the cliff.

2.3.3. Beach and Dune Erosion

Beach erosion was observed to take two forms. In some instances, sand and debris were pushed inland, while in others sand was carried offshore. Where sand was carried offshore, beach recovery is already occurring (i.e. at Horseshoe Bay), and is expected to continue over the next few months. At several locations, sand dunes were severely cut back (by up to 20-30 metres). The recovery process on sand dunes is slower than beaches, since it depends on the movement of above-water beach sand to the back of the beach by aeolian processes, followed by consolidation. This process may be expected to take a number of years, but may be aided by the application of dune fencing.

2.3.4. 'Setback' Policies

Hurricane Fabian demonstrated the importance of appropriate set back distances between buildings and the shoreline, and the consequences of inadequate setbacks. In some cases, swimming pools were filled with rock and debris from the seabed. In other cases, buildings that were located too close to the ocean were badly damaged by waves. The amount of setback to be used will depend primarily on the slope of the shoreline, the nearshore bathymetry, the rate of erosion of the shoreline and the geotechnical stability of the rock strata along the shoreline. While existing developments are already too close to the shoreline, this must be considered in the siting of new developments.

2.2 Use of the Coastal Erosion Vulnerability Assessment

Coming out of the *Coastal Erosion Vulnerability Assessment, Final Report*, extensive wave modeling results were made available. This wave modeling considered waves approaching from a variety of directions and included both day to day and hurricane waves. The results indicated that the south shore is generally much more exposed to wave action than the north shore. One of the reasons for this being that the north shore gains protection from the lagoon to the north. In addition, the most damaging waves appear to come from the south.

Specifically, the findings of the wave modeling have been applied to Section 4.1 of this document, Inundation and Setbacks, where the determined nearshore wave height and static storm surge levels for the 150 year storm, and wave run-up predictions have been combined and used to indicate inundation levels at various shoreline locations (and types) around the island.

3. Appropriate Shoreline Protection

This section of the document is intended to provide background information on the general **options for shoreline protection**, and to outline the **types and forms of structures** that are suitable for Bermuda. Both hard and soft shoreline protection solutions are discussed, including seawalls, revetments breakwaters and dune restoration.

General **design criteria** to be considered for shoreline protection structures in Bermuda are presented in Section 3.3.

It should be noted that this information is provided to guide the consideration for approval of shoreline protection works in a general sense only. Applications should be reviewed on a case by case basis, and should take into account the geological, biological and oceanographic conditions specific to the location.

3.1.Nature vs Protection

By their very nature coastlines are dynamic -they have been changing as long as there have been coastlines. However, as populations have grown, and the demand for seaside development has increased, there has been greater pressure to 'protect' shorelines from the forces of nature. Some argue that attempts to subdue or contain the ocean are futile given the magnitude of the wind and wave forces active along coastlines. They believe that instead of interfering with the dynamics of coastlines, nature should be allowed to take its course and develop away from the active forces of the shore, as nature will inevitably win.

On the other hand, in places such as Bermuda where landspace is finite and subject to the forces of erosion, there is an imminent need to armour the shoreline in order to protect life, property and infrastructure. A balance must therefore be sought in islands such as Bermuda between respecting the forces of nature and protecting human life and assets.

The key to achieving this balance is to ensure that the approach to armouring and development along the shoreline is cognizant of the forces of nature acting in the particular locations during a period of time.

The following photographs illustrate a spectrum of shoreline protection choices employed in the same general area and under similar coastline conditions. The protection choices range in these examples from natural to obviously man-made.

A high seawall, with substantial, flat landfill behind it. Not generally in keeping with the Bermuda Image, and the considered to be at one end of the shoreline protection spectrum.

A low seawall with sloping land behind it (no backfill). More in keeping with the Bermuda Image, and mid-way to minimal on the shoreline protection spectrum.

Natural landscape, with sloping coastline, and substantial vegetation. In keeping with the Bermuda Image, and the natural end of the shoreline protection spectrum.

3.2. Shoreline Protection Structures

3.2.1. Seawalls

A seawall is a free-standing structure built parallel to the shoreline with the purpose of separating the land and water so as to protect against erosion and other wave induced damage. Seawalls are typically constructed from concrete or quarried stone, and can take a range of forms including a smooth vertical face, a stepped face or a curved face (Figure 3.1).

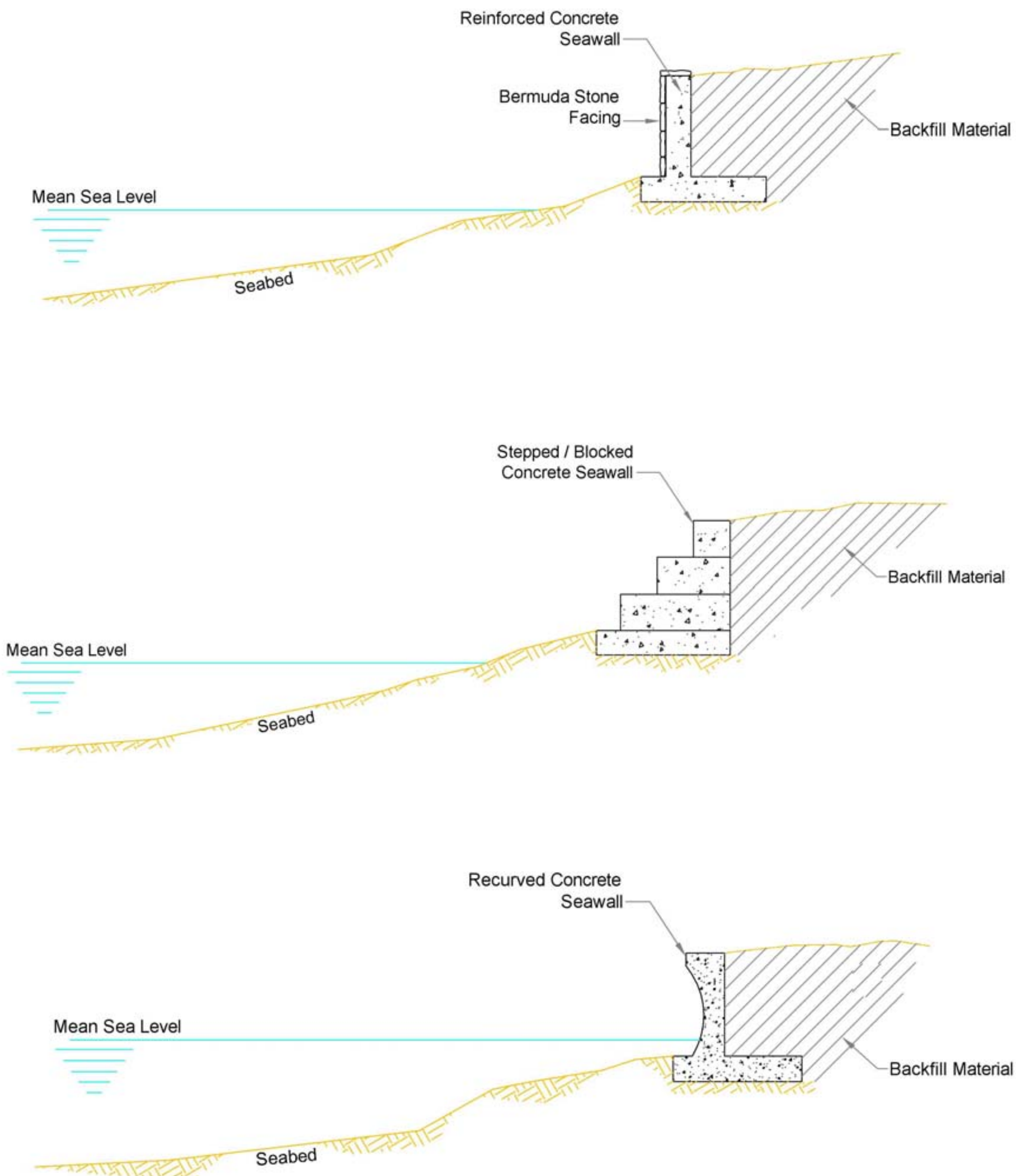

Figure 3.1 Generalized Cross-sections of a Seawall (Vertical, Stepped and Curved)

Well designed and constructed seawalls can provide good protection to property, and may improve boat access to the shore. However, seawalls are known to have a negative effect on fronting beaches, where waves reflected from the wall tend to cause an increase in erosion in front of the structure. As such, they are not recommended in beach areas. Furthermore, a seawall protects only the land immediately behind the structure, and adjacent land may typically experience increased rates of erosion.

General design considerations for a seawall should include the foundation, drainage, prevention of scour, materials, the effects on coastal processes, and the impacts on recreational activities (waterfront access).

3.2.2. Revetments

A revetment is a structure built at and parallel to the toe of a bluff, embankment or scarp, or at the back of a beach, with the intention of protecting the slope against wave action. Revetments can be constructed from a variety of materials including concrete, quarried armour stone or gabions, and may be rigid or flexible (rip-rap or interlocking blocks) in form (Figure 3.2).

Revetments result in less depletion of fronting beaches than seawalls and are generally less affected by scour. However, like seawalls, revetments do not provide protection for adjacent areas, which may actually experience increased erosion as a result of wave reflection from the revetment.

General designs for a revetment should include a consideration of the main components of the structure, namely the filter layer (if applicable), the armour layer and the toe protection. The sizing of these individual components is based on a knowledge of the nearshore wave climate.

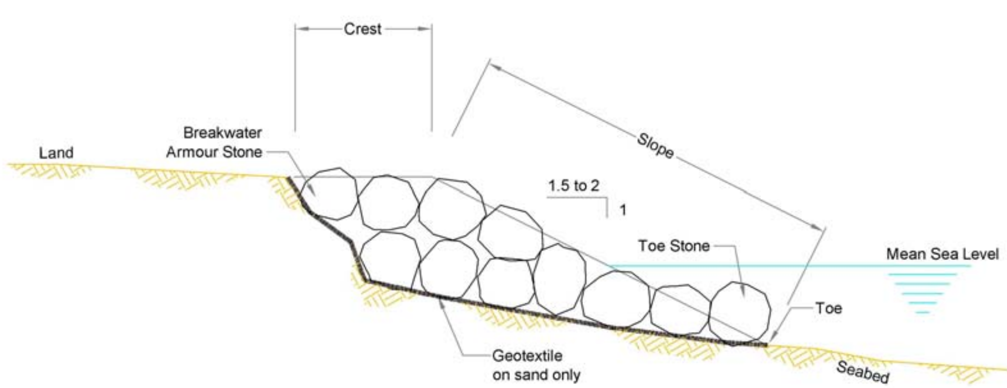

Figure 3.2 Generalized Cross-section of a Revetment

3.2.3. Breakwaters

Breakwaters are structures constructed either offshore from, or connected to the shoreline, with the objective of protecting the shore from wave action and/or to create calm water for the purpose of boat mooring or recreational activities. They are usually aligned parallel to the shore, although they may be slightly angled depending on wave conditions (Figure 3.3). As a secondary function, breakwaters can provide erosion control by dissipating and deflecting wave energy from an otherwise high-energy shoreline.

Breakwaters can be either floating or bottom-founded, and they can be constructed from concrete (e.g. a caisson) or quarried armour stone. However floating breakwaters may be of only very limited use in Bermuda as they are not effective for larger period waves. The benefits of breakwaters usually extend over a relatively long area of shoreline, however, they may also result in erosion on the downdrift side, unless carefully designed to minimize this effect.

The design of breakwaters should consider:

- The incident wave climate (height, period and direction).
- The use of quarried armour stone or concrete armour.
- The area of shoreline to be sheltered.
- The optimum length of breakwater structure.
- The optimum distance offshore of this structure so as to minimize the formation of a tombolo.
- The spacing between breakwaters, where multiple structures are used.
- The prevailing current patterns and the impact of these structures on these patterns.
- The effect on adjacent shorelines.

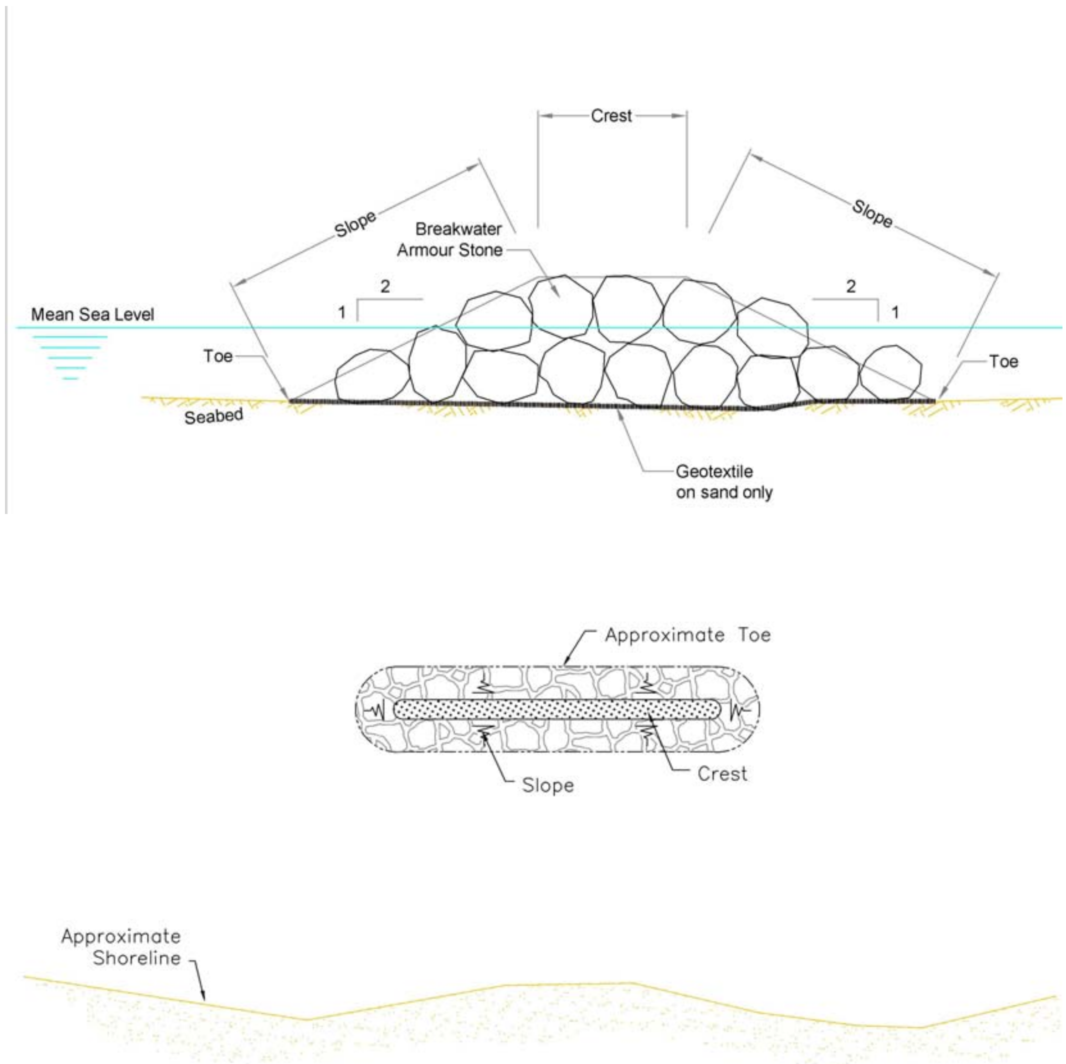

Figure 3.3 General Cross-section (top) and Plan (bottom) of a Breakwater.

3.2.4. Dune Restoration

Coastal sand dunes serve as natural sand reserves for beaches and also offer a physical barrier to storm waves. They are essential in preventing long-term erosion of beaches and of areas further inland. However, sand dunes are themselves subject to erosion from both wind and wave forces. Dunes are therefore only maintained or built when there is an obstruction to these forces.

There are two main methods of artificially creating dunes in sandy areas. The first is a mechanical method characterized by implementing fences or windbreaks. These fences are typically made of wooden slats or plastic netting.

The second method is a vegetative method which involves the planting of sand and salt tolerant species and using these to reduce the impacts of wind and for trapping the sand.

There are a number of factors to be considered in the artificial creation of dunes. The porosity of the fencing should be determined, and it is suggested that nothing less than 50% porosity be applied. The recommended ratio of solid to open spacing in the fence should be 80:20. Consideration should also be given to the spacing of the slots and the fences themselves.

3.3. Shoreline Protection - Design Considerations

Based on the findings of the Coastal Erosion Vulnerability Assessment and the observations made during the Hurricane Fabian Damage Assessment, several design issues have been identified that require particular consideration for the implementation of coastal protection structures in Bermuda. In the application of these issues to the planning and approvals process, they will need to be considered on a case by case basis and may need to be modified for specific individual sites.

3.3.1. Minimum Design – Water Levels, Wave Height and Runup

It is necessary to determine the water level and wave heights that the desired structures will be expected to withstand. Shoreline defense structures that are protecting houses, roads, hotel developments and other important infrastructure should be able to withstand the **1 in 50-year storm event**.

The wave forces from the 1 in 50 year design event must be established in the design process for specific sites, as they will depend on the local conditions. These forces must be determined statistically from an analysis of the predicted water levels, wave heights and storm surges. Application of these loads to the design of a coastal structure should be carried out by a qualified Professional Engineer.

3.3.2. Foundations

In general, a structure is only as good as its foundation, and so the structures must be designed and built taking the foundation into consideration. Sandy substrate is very prone to erosion, and so structures built in sandy areas are more prone to undercutting. The foundations of structures in sandy areas should therefore extend below the depth to which wave scour is expected to occur. For structures on rocky shores the foundations should be keyed into the solid rock, or appropriately dowelled in.

3.3.3. Flank and Toe Protection

Some shoreline protection structures such as seawalls and revetments are susceptible to the erosion progressing around the ends. This 'flanking' can be prevented by constructing returns at the end of the structures, to tie them properly back into the shoreline.

Many of the cases of failure in coastal protection structures results from wave scour and the undermining of the toe of the structure – that area at the front and bottom of the structure, closest to the water. Toe protection, or armouring of the structure, is necessary to prevent this. As such, the structures should be designed to extend far enough into the bottom not to be undercut by wave action.

If a seawall is not to be founded on rock (an undesirable situation), then it will be necessary or desirable to construct a scour apron in front of the wall at its toe.

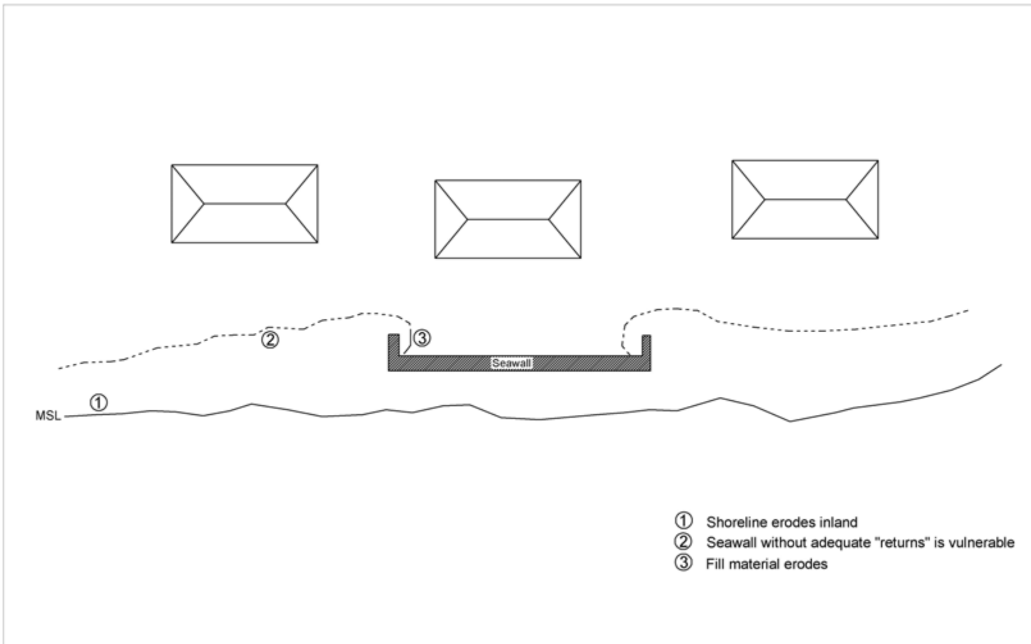

Figure 3.4 Typical Mode of Seawall Failure – Flank Failure

3.3.4. Drainage

Adequate attention must be paid to drainage for design of any structure along the shoreline. Measures must be put in place to allow water to flow quickly and easily to the sea with limited adverse impact on the structure. The drainage system must prevent build-up of water behind the structure and must channel the water in a controlled manner through the runoff ports. The design of such drainage systems however, must also ensure that the runoff ports do not allow more inflow than outflow of seawater.

3.3.5. Materials

Concrete used in marine conditions should be designed to have a developed strength of not less than 5000 pounds per square inch (psi). Adequate concrete cover should be provided to prevent corrosion of steel.

3.3.6. Finish of Structure

Proper attention must be paid to aesthetics particularly in keeping with the Bermuda Image. For seawalls, this may include facing with Bermuda stone or stepped structures. For repairs of failed cliffs, a surface texturing using moulds, or gunite and colouring of the concrete should be used to match the appearance of the adjacent natural stone. Several examples of Bermuda stone facing were observed to have withstood the wave impacts of Hurricane Fabian. Consideration should also be given to landscaping of the structures (for example, vegetation on top of revetments).

Figure 3.5 Retaining wall in keeping with the Bermuda Image

4. Appropriate Shoreline Development

The lessons learned from Hurricane Fabian, and the findings from the coastal erosion vulnerability assessment have together provided significant direction for the considerations to be given to shoreline development in Bermuda. Among the concepts to be applied to coastal development is the establishment of setbacks or minimum floor elevations, including the determined inundation levels, the adoption of a community approach to shoreline defense, and the importance of function over aesthetics.

4.1. Inundation and Setbacks

The wave modeling results combined with the shoreline orientation and type (presented in the Coastal Erosion Vulnerability Assessment, Final Report), led to the division of the Bermuda shoreline into thirteen (13) sections (see Figure 4.1). For each section, a range of values of nearshore wave height and static storm surge were computed (Table 4.1) for both the 50 year and 150 year hurricane events (by comparison, Hurricane Fabian is estimated to have been greater than a 100 year event but less intense than a 150 year event).

This information was combined with wave run-up calculations to give an indication of inundation levels (see storm surge and wave run-up definitions in Figure 4.2). These findings may therefore be used as a tool to regulate building location and elevation at, or close to, the shoreline using information from Table 4.2, and may be applied to infer appropriate setback distances for development on different shoreline types defined in Figure 4.3.

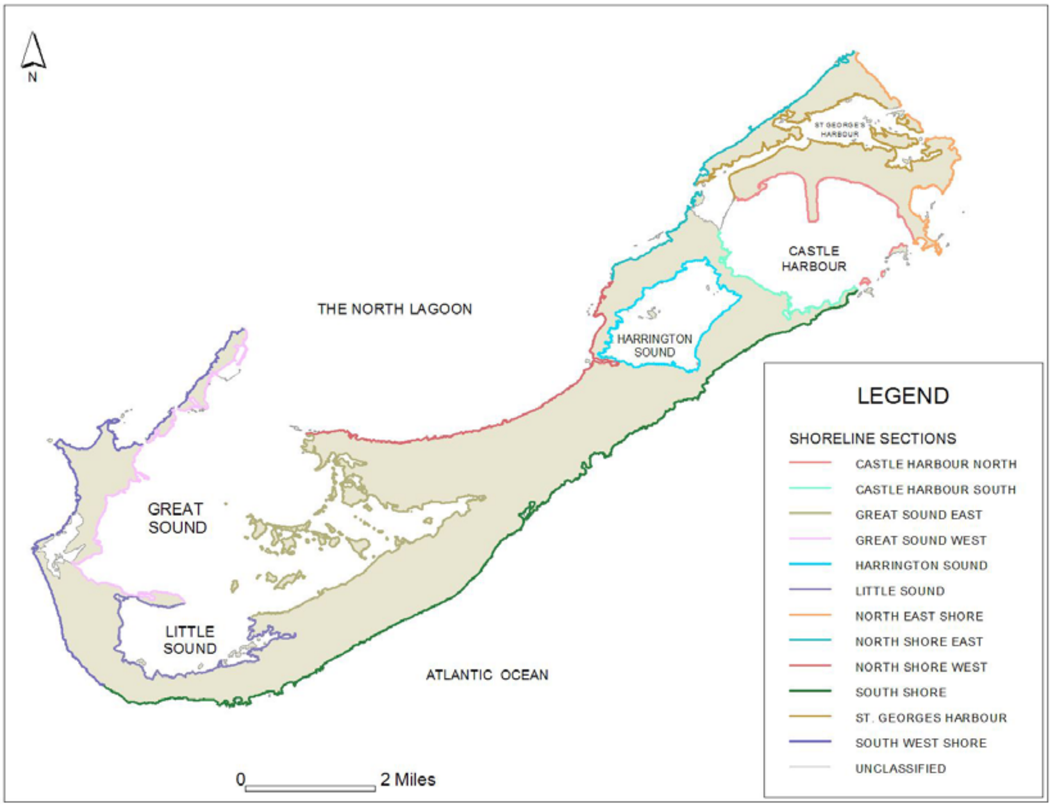

Figure 4.1 **Division of Shoreline by Maximum Wave Heights, Orientation and Type**

Table 4.1 **Wave Height and Storm Surge by Shoreline Section**

Location	Wave Height in 10m-depth		Static Storm Surge at Shore	
	50-year	150-yr	50-year	150-yr
North Shore - East	3.0-3.5	4.0-6.0	1.3-1.4	1.6-1.8
North Shore - West	2.5-5.0	3.0-5.0	1.4-1.5	1.8-2.0
West Shore	3.0-4.0	3.0-5.0	1.4-1.6	1.8-2.0
South West Shore	2.5-4.0	3.0-5.0	1.6-1.8	2.0-2.3
South Shore	5.0-8.0	5.0-8.0	1.7-1.9	2.0-2.2
North East Shore	3.0-7.0	3.0-7.0	1.5-1.7	1.7-2.1
St. Georges Harbour	1.5-2.0	1.5-2.5	1.4-1.5	1.7-2.0
Castle Harbour - North	2.0-3.0	2.5-4.0	1.7-1.8	2.0-2.3
Castle Harbour - South	1.5-2.5	2.0-2.5	1.7-1.9	2.0-2.3
Harrington Sound	1.5-2.5	1.5-2.5	1.4-1.5	1.8-2.0
Great Sound- East	1.5-2.0	2.0-3.0	1.4-1.5	1.7-1.8
Little Sound	1.5-2.5	2.0-3.0	1.4-1.5	1.7-1.9
Great Sound-West	2.5-4.0	2.5-4.0	1.4-1.5	1.7-1.9

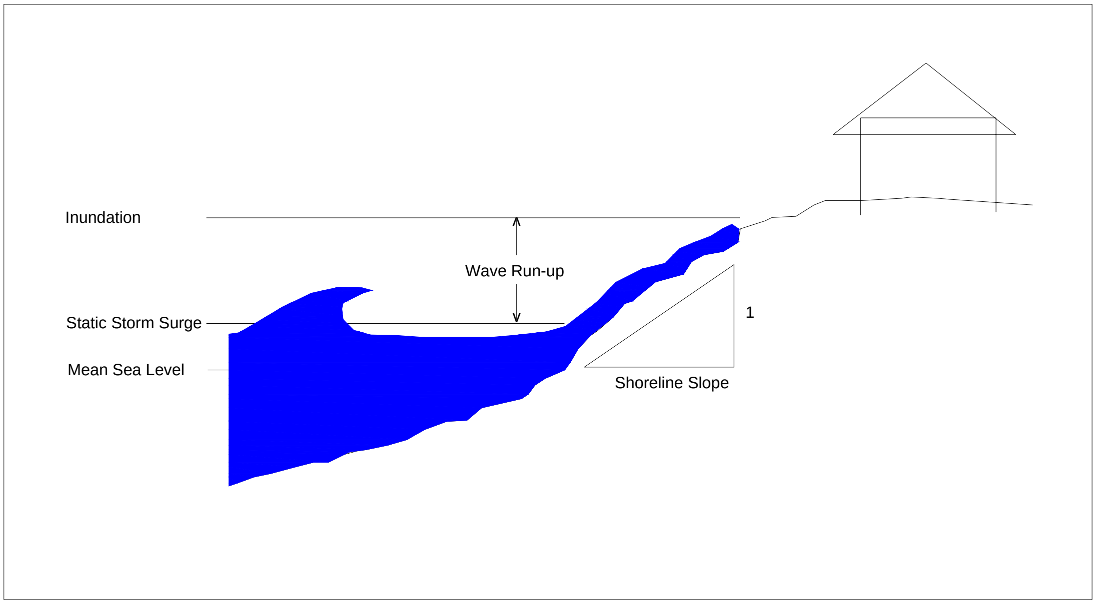

Figure 4.2 **Definition sketch for calculation of Inundation Levels**

Table 4.2 **Inundation levels by Shoreline Section**

Location	Inundation Levels above Mean Sea Level (MSL)			
	Beach	Flat Rock	Low Cliff	High Cliff
North Shore - East	4.4-6.2	3.0-4.4	5.3-7.1	7.1-9.4
North Shore - West	4.6-6.4	3.2-4.6	5.3-7.3	7.3-9.6
West Shore	4.6-6.4	3.2-4.6	5.5-7.3	7.3-9.6
South West Shore	3.0-5.1	2.6-3.9	3.3-5.7	3.9-7.2
South Shore	5.1-9.6	3.3-6.6	6.9-11.1	9.3-14.9
North East Shore	4.6-6.4	3.2-4.6	5.5-7.3	7.3-9.6
St. Georges Harbour	2.7-4.8	2.3-3.6	3.0-5.4	3.6-6.8
Castle Harbour - North	4.8-6.6	3.4-4.8	5.7-7.5	7.5-9.6
Castle Harbour - South	3.0-5.1	2.6-3.9	3.3-5.7	3.9-7.2
Harrington Sound	2.8-4.9	2.4-3.7	3.1-5.5	3.7-6.9
Great Sound- East	2.6-4.7	2.2-3.5	2.9-5.3	3.5-6.7
Little Sound	2.7-4.8	2.3-3.6	3.0-5.4	3.6-6.8
Great Sound-West	4.5-6.3	3.1-4.5	5.4-7.2	7.2-9.5

Sandy shorelines (beaches) are found mostly along the south of Bermuda, although there are some pocket beaches along the north and east coasts and the interior shorelines.

Flat rocky coastline refers to low-lying, relatively flat, rocky coastline with typical elevations occurring between sea level and 1 meter above MSL. These are found mostly along the north-central coast.

Low cliffs are represented by steep rock faces between 1 and 7 meters high and are found at various locations around the island, including the north-east coast and the south coast.

High cliffs are represented by vertical rock faces greater than 7 meters and are found mainly along the eastern and south-eastern areas of the island.

Figure 4.3 Shoreline Types around Bermuda

4.1.1. Use of the Inundation Table

Two approach streams are possible for using the information that has been provided above. These are outlined following:

1. ***The Approximate Approach***

This approach gives the planner/developer a good first estimate of the wave and water level conditions offshore the point of interest. Use Figure 4.1and Table 4.2 to get an estimate of the possible range of inundation levels at the particular site. This requires knowledge of the type of shoreline classification at the site (i.e. beach, low cliff, high cliff etc.)

2. ***The Detailed Approach***

This approach requires more detailed analysis than the first, but it also allows a narrowing of the range of inundation levels from those given in Table 4.2. It requires the input of a qualified Engineer.

Step 1 → Identify the site location from within the thirteen (13) sectors shown on Figure 4.1.

Step 2 → Extract from Table 4.1, the applicable values of wave height and static storm surge at the shoreline, for the 150 year event.

Step 3 → Carry out wave transformation computations, to arrive at the wave height just offshore the site location.

Step 4 → Using the wave height computations at the shoreline, evaluate the wave run-up, using site specific slope information. The wave run up should then be added to the static storm surge.

4.1.2. Example of Inundation Determination, South Side

The housing development in South Side, St. George's Harbour is to include construction of approximately 200 houses. Because of the susceptibility of this area to storm surges during hurricanes, it is necessary to quantify the expected levels of storm surge. As such, the following are to be derived in this assessment:

- Expected storm surge values along the development's shoreline during severe hurricane events;
- The shoreline's susceptibility to hurricane wave and storm surge erosion;

The shoreline is presently comprised of mainly rubble and debris. Most of the shoreline is about 3m above mean sea level. The existing shoreline is graded almost vertically. Without proper armouring, the shoreline is prone to significant erosion from hurricanes.

1. ***The Approximate Approach***
   a. Refer to Table 4.1

   - Location: St. Georges Harbour
   - Wave Height for 150 year event = 1.5 - 2.5 m

   b. Refer to Table 4.2

   - Inundation Level – Low Cliff Shoreline = 3.0 – 5.4 m

2. ***The Detailed Approach***
   a. Refer to Table 4.1

   - Wave Height for 150 year event = 1.5 – 2.5 m

   b. Carry out wave transformation analyses (Figure 4.4) :

   - Storm surge prediction (static) = 1.9 m

   c. Carry out Wave Run-up Analysis (Figure 4.5)

   - Wave run-up = 2.04 m

   d. Derive Total Inundation levels for the South Side location.

   - Inundation = 1.9 + 2.04 = 3.94 m

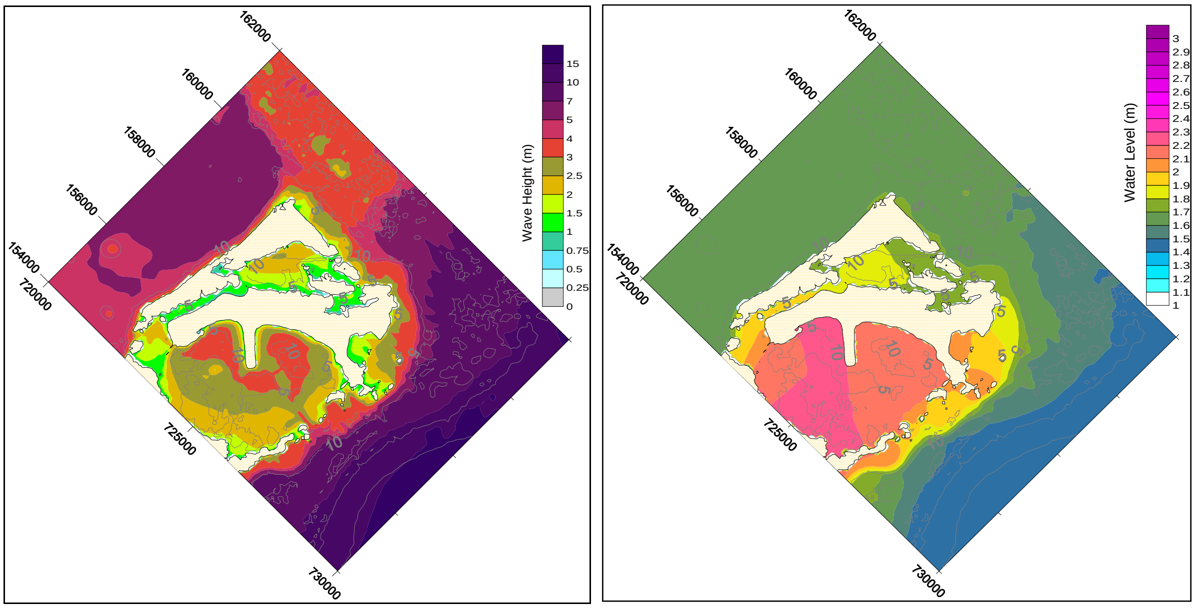

Figure 4.4 1 in 150-year Hurricane Waves 1 in 150-year Hurricane Storm Surge (Static)

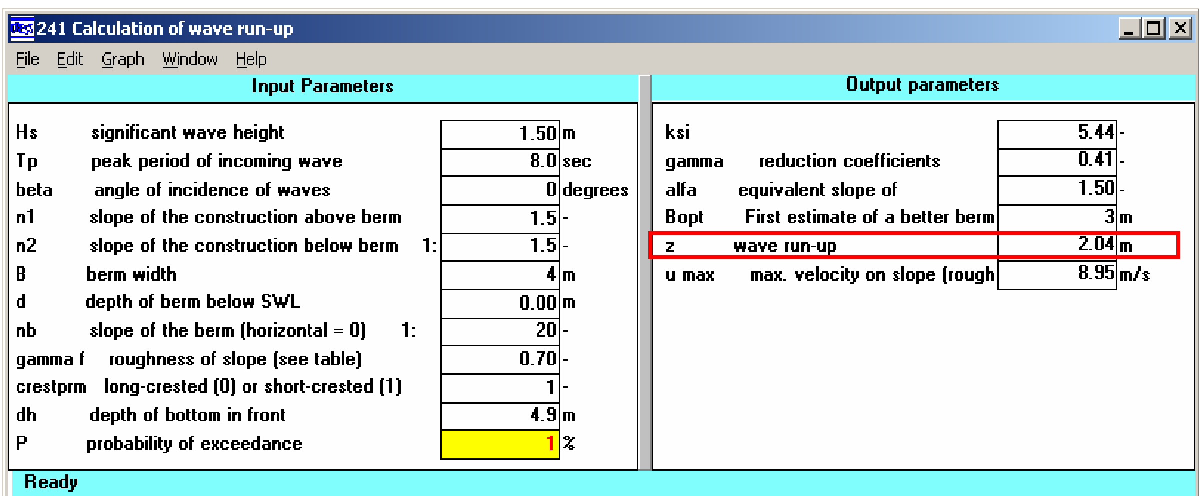

Figure 4.5 Example of Wave Run-up Calculation

4.2. Other Shoreline Development Considerations

4.2.1. General considerations

There are several other issues that need to be considered for shoreline development in Bermuda. Among these is the need for a "community" approach to the implementation of appropriate protection, i.e. consistent solutions should be applied along a particular stretch of shoreline. In addition to having consistent solutions along a shoreline, the neighbouring structures should be joined together (one structure) to avoid vulnerabilities at a structure's flank, or boundary. This requires neighbouring property owners to work together for the stability of the entire shoreline.

Also, consideration to the form of structures should primarily relate to function. The aesthetics, while important, should be secondary.

Some of the specific shoreline development considerations include:

- Along the south shore where beaches are backed by cliffs, any structure located on the beach should be regarded as "temporary", due to the magnitude of wave forces that can be expected.
- In all cases, vegetation should be encouraged along dunes as a form of protection.
- Structures built on sand dunes should be founded below the expected scour depths (which can be computed using wave height information at the shoreline).
- In areas where cliffs are undermined, they may be packed with stones and grouted with concrete.
- In areas where there is limited opportunity for substantial foundations revetments should be considered as opposed to seawalls.
- In cases of reclaimed land, revetments are encouraged.
- In areas where the waves are not the primary erosion agent, such as the inland waterways, seawalls can be considered.
- Public infrastructure such as coastal roads and bridges (e.g. the causeway) must be armoured with sloping rock or concrete units able to withstand severe wave forces. These units will help to dissipate most of the wave energy.

4.2.2. Seawalls

Given their prominence along the Bermuda shoreline special attention must be paid to the construction of seawalls. Specifically, for the conditions in Bermuda a number of details must be included in the **design and construction of seawalls** (i.e. those that will be subject to wave forces during their lifetime). These include:

- Foundations should be keyed into solid rock;
- Steel reinforcing should be incorporated into the structural design;

- Seawalls must be "tied in" to adjacent structures, rock outcrops, or should have adequate returns to prevent flank failure;
- Stone balustrades and other features not fixed to a seawall should be avoided, as these can become projectiles in a hurricane, that will cause additional damage;
- Stepped or sloping structures should be encouraged (but not made mandatory), as long as proper engineering designs are carried out;
- Care should be taken when constructing new structures atop (old) existing ones. The structural integrity of new structures depends greatly on that of the existing (old) structure.

4.2.3. Biological Erosion – Further Research

In areas such as Harrington Sound where the erosion is caused by biological forces, further research needs to be conducted into the eroding organisms to determine their biology and ecology for the development of appropriate management strategies. Until such research and plans are developed, shoreline protection should be considered.

4.2.4. Jetties and Docks

Jetties and docks may be constructed where berthing of vessels is to occur. These structures may be built from timber, concrete or plastic polymer.

Jetties and docks should ideally be located in areas where wave heights are less than 0.3m for 97-99% of the time. These requirements ensure that no breakwater structure will be necessary.

5. Ecological Concerns

This section is intended to present and provide general information on ecological issues that should be considered in the management of shoreline development and protection in Bermuda.

5.1. Casuarina

One of the apparent contributors to the erosion of the rocky areas of Bermuda is the Australian pine tree, *Casuarina equisetifolia*. The *Casuarina* tree was introduced to Bermuda in the 1940/50's to replace the blighted native Bermuda cedar as a windbreak. The species was selected based on its salt-tolerant, evergreen and fast-growing characteristics, and it has thrived in Bermuda.

The problems with the trees are related to the root structure of the plants, coupled with the reproduction mechanisms of the species. The roots of the trees are thick and shallow, and are able to anchor the plants in areas with very little soil. As such, the trees grow well in the soft rock of the Bermuda shoreline, using crevices to access nutrients and support. The result is that the soft rock chips and breaks from the penetration of the *Casuarina* root, thereby eroding the rock. Additionally, because of the height of the trees (up to 70 – 90 feet) and the shallowness of the roots, the species is very susceptible to being uprooted and blown around during strong winds and hurricanes, further breaking up the soft rocky shoreline.

Compounding the damage caused by the root penetration, the *Casuarina*, an angiosperm, can flower year round; uses wind as a pollinating agent, produces tremendous numbers of winged seeds, and is a prolific reproducer. Seedlings and saplings are abundant in Bermuda, and small *Casuarina* forests have grown in some areas of the islands. The species has turned out to be more of a burden on the ecology and stability of the island, rather than a useful windbreak.

In order to address the problem of the *Casuarina*, and to mitigate the erosion caused by these trees, an appropriate Eradication Programme and Public Awareness Campaign need to be developed. These initiatives should seek to remove the *Casuarina* in the coastal areas and replace them with an endemic species such as the Bermuda Cedar.

5.2.Rock Borers – Harrington Sound

The action of boring and grazing organisms such as gastropods, bivalves and worms living in rocks within the intertidal zone removes significant rock material over time to form a distinct notch along the coastline of Harrington Sound. These notches extend up to 5 meters inland and undermine the rock which will eventually collapse.

Research needs to be conducted into the specific eroding organisms in Harrington Sound to determine their biology and ecology in order to develop appropriate management strategies. Until such research and plans are developed, shoreline protection will need to be considered on a case by case basis.

5.3. Coral Reefs

There are three main types of reefs found around Bermuda:

1. **The patch reefs** in the North Lagoon. These reefs are adapted to the relative calm of the shallow lagoon waters, being protected by the outer reefs of the Bermuda platform. The composition of these reefs is more varied than other reefs around the islands, having boulder corals, some branching corals (*Madracis, Oculina, Millepora*), and soft corals (*Pseudoplexaura*).
2. **The rim reefs**, which circle the edge of the North Lagoon, and mark the outer rim of the Bermuda platform. These reefs are more exposed to wave action than the patch reefs, and so tend to be comprised mostly of hard, boulder corals (brain and star), and some soft corals (sea rods and sea fans).
3. **The boiler reefs,** which are found on the south and southeastern sections of the platform, and are continuously impacted by waves. The corals on these reefs tend to be small rounded species, and act as significant breakers of the incoming waves.

The importance of these reefs, and in particular the rim and boiler reefs, to the protection of Bermuda's shoreline cannot be overstated. Their dominance of the coastal zone, and their role in slowing day to day wave action and dissipating wave energy is vital in maintaining the sandy and rocky shorelines of the islands. Without the reefs, the wave energy reaching Bermuda's shores would be much greater, and have a major effect on the stability of the islands.

Based on their extremely important role in the protection of the shoreline, it is essential that the health and structure of these reefs be maintained. Planning and development decisions should therefore consider the conservation and protection of Bermuda's coral reefs. Concerns outside the scope of this project need to be addressed such as nutrient loading and possible pathogens.

6. References

The Bermuda Plan 1992

Smith Warner International, 2004. Bermuda Coastal Erosion Vulnerability Assessment, Final Report.

Smith Warner International, 2003. Assessment of Coastal Damages Following Hurricane Fabian.

Appendix I

The following is an excerpt from SWI's response to the Request for Proposal (RFP) for the Bermuda Coastal Erosion Vulnerability Assessment, which also formed a part of Appendix 3 of the Memorandum of Agreement for the project.

Scope of Work

The Bermuda Government Department of Planning (BGDP) is interested in having a study of coastal erosion in Bermuda conducted, in order to identify those areas around the island most at risk for erosion, and to develop policies for protecting the coast accordingly. Specifically, BGDP is interested in the following:

1. A synthesis of the data that already exists in Bermuda about coastal erosion;
2. A determination of which coastal areas in Bermuda are prone to erosion and which structures and landforms are most at risk;
3. Recommendations of best practices for coastal development and conservation.

Methodology

Based on the Scope of Work and the required outputs, our approach can be divided into a number of discrete tasks, which are described below:

Task 1 – Site Reconnaissance, Existing Data Collection and Review

This task will consist of a one to two week site visit by key members of the team, to familiarize themselves with the problems facing Bermuda. In addition, all of the existing relevant data will be collected and reviewed at this time. Discussions will be held with personnel from the Department of Planning so that the core issues of concern to the Department may be fully addressed in the project.

Beaches and threatened cliffs will be visited and sediment samples will be collected. If not already in place, a programme of beach profile monitoring must be started to properly assess any trends of shoreline erosion. Typically, these beach profile monitoring programmes involve regularly repeated measurement at a particular site over a number of years. The results of a first set of beach profiles will be used in the shoreline process modeling. Shorelines that are characterized by cliffs will also be visited to determine their general condition and susceptibility to erosion. In addition, meetings will be held with the

Bermuda Biological Station for Research, as to the status of ecosystems in the marine waters of Bermuda. A summary of the work to be carried out in this 1-2 week period is given following:

- Discussions with relevant personnel in the Department of Planning;
- Discussions with all other appropriate agencies;
- Collection and collation of available background data;
- Assessment of data strengths, weaknesses and gaps;
- Development of a shoreline inventory, noting shoreline types/characteristics; existing structural interventions; areas most threatened; ecosystem conditions; classification of shoreline from coastal process and user perspectives. This inventory will be informed by available aerial photography;
- Commissioning of a series of quarterly beach profile surveys, using a surveyor recommended by the Department of Planning. These data will be used to allow the Department of Planning to assess annual/seasonal fluctuations, as well as long-term trends in beach width (accretion or erosion);
- Under this task, we will advise as to the most appropriate locations for beach profiling, the setting up of permanent benchmarks, and the identification of an appropriate agency to be responsible for continuing the programme;
- Final Client meetings prior to departure, to summarize progress made under the site reconnaissance task.

In addition to the tasks outlined above, we will review some of the applications presently being received by the Department of Planning, in order to obtain a first-hand appreciation of the range of shoreline development and protection concepts that are presently being considered for implementation in Bermuda.

Task 2 – Hurricane and Storm Susceptibility

The island of Bermuda is exposed to waves coming from all directions. These waves arise from extra-tropical Atlantic storms, tropical cyclones, and from the North-Easterly Trade Winds. The most severe waves, however, are likely due to hurricanes. Along with these severe wave conditions, storm surge due to wind and wave set-up and inverse barometric rise can be expected to increase the mean water level by up to approximately 2 metres. Under this task, we will develop a "wave climatology" or description of the wave conditions applicable to this shoreline. Data sources that will be used to develop this climatology will include the NOAA database of hurricane storm tracks, as well as archived results from a global wave model. Together, these data sources will provide both design (hurricane) and operational (wave model) wave conditions. Once this database of wave conditions has been assembled, a wave refraction-diffraction analysis will be performed to define inshore wave conditions for the Bermudian shoreline. This information will assist in the creation of different coastal erosion vulnerability zones. Bathymetric data, which will facilitate the transformation of deep-water waves in to the shoreline areas, will be obtained from existing hydrographic charts, augmented by specified beach profiles.

Task 3 – Shoreline Process Modeling

Using the inshore wave conditions developed in Task 2, shoreline process modeling will be undertaken using the DHI *Litpack* suite of software. This computer software will be used to assess alongshore sediment transport patterns, including annualized rates and pathways. In addition, Litpack will be used to determine the cross-shore erosion that occurs during design hurricane events. This erosion will be used to guide the recommended setback distances. A full description of the Litpack software suite is included as Appendix 2 – Model Descriptions.

Task 4 – Coastal Erosion and Risk Map Preparation

The results of Tasks 1, 2, and 3 will be used to prepare draft coastal erosion and risk maps. These maps will be prepared using the best available base mapping (ortho-rectified air photos from 1997). Results showing areas of differing erosion risks and the vulnerability of existing infrastructure will be shown in ArcView maps. These maps will also be printed in hard-copy format and submitted to the Government of Bermuda for review and comments.

Task 5 – Ground-Truthing Site Visit

Following the preparation of coastal erosion and risk maps, a more extensive site visit will be made to ground-truth these maps. As a result of this ground-truthing exercise, changes to the erosion and risk maps will be noted so that updates can be made. Any such changes will also incorporate comments received from the Government reviews.

Task 6 – Preparation of Coastal Development Guidelines

A comprehensive set of guidelines for assessing coastal development applications will then be prepared for the Department of Planning. These guidelines will address the issues of typical shoreline protection, stabilization, enhancement and maintenance. In addition to these guidelines, typical designs for the most appropriate shoreline protection will be prepared for different shoreline types. These guidelines will be presented in a manner compatible with the Draft Bermuda Development Plan.

Task 7 – Seminar: Coastal Development Guidelines

This task will involve the presentation of the final coastal development guidelines to members of staff at the Department of Planning. A two-day seminar is envisaged, covering some of the basics of coastal engineering design as well as working through some examples and/or existing applications.

Task 8 – Final Report Preparation

A comprehensive final report will be prepared documenting all of the investigations, methods used, feedback from the seminar and results obtained.